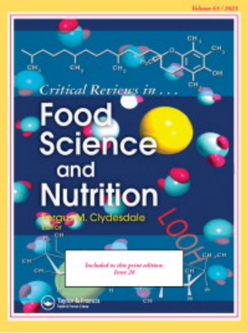

Critical Reviews in Food Science and Nutrition

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/bfsn20

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To cite this article: Dietrich Knorr & Mary Ann Augustin (2023) Preserving the food preservation legacy, Critical Reviews in Food Science and Nutrition, 63:28, 9519-9538, DOI: 10.1080/10408398.2022.2065459

To link to this article: https://doi.org/10.1080/10408398.2022.2065459

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
2023, VOL. 63, NO. 28, 9519–9538
https://doi.org/10.1080/10408398.2022.2065459

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REVIEW

Preserving the food preservation legacy

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ABSTRACT
This paper deals with the question about how early humans managed to feed themselves, and how they preserved and stored food for times of need. It attempts to show how humans interacted with their environments and demonstrate what lessons can be learnt from the about 3.4 million years of food processing and preservation. It includes a discussion about how hominins shifted from consumption of nuts and berries toward meat and learnt to control and use fire. Cooking with fire generated more food-related energy and enabled humans to have more mobility. The main trust of the paper is on historical food preservations, organized from the perspectives of key mechanical, thermal, biological and chemical processes. Emerging food processes are also highlighted. Furthermore, how humans historically dealt with food storage and packaging and how early humans interacted with their given environments are discussed. Learnings from the history of food preservation and culinary practices of our ancestors provide us with an understanding of their culture and how they adapted and lived with their given environments to ensure adequacy of food supply. Collaboration between food scientists and anthropologists is advocated as this adds another dimension to building resilient and sustainable food systems for the future.

KEYWORDS
Food preservation; processing tools and unit operations; early humans; food anthropology; resilient food systems

Introduction

> *"Tradition ist nicht die Anbetung der Asche sondern die Weitergabe des Feuers" (Tradition is not the worship of the ashes but passing on the fire).* Gustav Mahler, Austro-Bohemian composer and conductor, 1860-1911

Food permeates all aspects of human life. The science of food is multi-disciplinary. The pathway from feed to food through the ages has multiple dimensions and crosses many discipline boundaries. Only a narrow perspective of food is possible when viewed through the lens of individual disciplines, such as agriculture, food science and technology, anthropology, social science, political science, economic, history, cultural sciences or social justice. Greater diversity of insights brought by different disciplines, considered in a more holistic way, is needed to shed light on the complexities for ensuring a secure future food supply.

The Cambridge World History of Food (Kiple and Ornelas 2000), is a comprehensive, multi-author resource for information on the tremendous diversity of foods around the world and a useful resource for food scientists, food anthropologists and social historians (Webb 2001) but it provides limited data about processing and preservation of food. The developments in modern food science have been built on knowledge through the ages. Today, the scientific developments in the preparation of foods are additionally based on perspectives of the physical and chemical properties of food, material science and engineering, and there is an understanding of how important they are for underpinning the art of culinary science (Aguilera 2017; Vega, Ubbink, and van der Linden 2012). The importance of the social aspects and pleasure provided by food, and the creativity, ingenuity, complexity, skills and sophistication in generating food (Gibney 2021) should be more fully appreciated.

Much can be gained by analysis of the failures and successes of how those before us dealt with food. Eating, food rituals and identities, diets, food insecurity and the inter-relationships between material, socio-cultural and nutritional-medical dimensions of food systems have been examined through anthropological perspectives on food (Chrzan and Brett 2019; Messer 1984; Mintz and Du Bois 2002; Shipton 1990). Since most foods and their raw materials are seasonal and/or prone to spoilage and commodities are also perishable, one wonders how our ancestors survived on the food supply available to them without the detailed scientific knowledge available today. What our ancestors ate in different parts of the world depended on what food was available to them in the regions and their climatic conditions, their ability to hunt proficiently, and to preserve and process foods (Food and Agriculture Organization of the United Nations and Alliance of Bioversity International and CIAT 2021; Garn and Leonard 1989; Nummer 2002). This raises the following questions: How did our ancestors process, preserve and store their food for survival throughout extended periods? How did they interact with their given

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environments? What can we learn from them and implement into current food systems?

To address these questions, we trace the history of how our ancestors and the generations following developed the pathway from raw materials to foods for consumption. We should be mindful that insightful ignorance, uncertainty and curiosity are important drivers of food systems science (Knorr and Augustin 2021a). This curiosity-driven review provides a historical perspective of how raw materials were processed and perishable foods preserved to avoid waste and to provision for an adequate supply of safe, healthy and sensorially acceptable foods in various environments. It discusses how the consumption of traditional foods by various communities have changed over the years due to the altered availability and affordability of foods and disruptions in lifestyle (Andronov et al. 2021; Erdkamp, Ryckbosch, and Scholliers 2019; Gan et al. 2020; Reyes-García et al. 2019). We explore insights developed over the years and examine how they may be used to guide and inform the development of current and future food systems.

Historical perspectives

Items from archeological finds

Items uncovered during excavation of archeological sites, such as tools, cooking and storage features used by humans at various times, are relevant to the history of processing of foods (Wright 2014). The oldest identified stone tools related to food processing date back to 3.39 million years (McPherron et al. 2010) and systematically flaked stone tools are dated to >2.58 million years ago (Braun et al. 2019; McPherron et al. 2010). The controlled use of fire and hearths was about 790 kyr ago, as evidenced by the findings in the form of burned seeds, wood and flint in Africa. Earliest evidence for habitual use of fire in Europe was about 300-400 kyr ago (Pobiner 2016; Roebroeks and Villa 2011) and also in various parts of the world from about 400 kyr ago (Gowlett 2016). There is evidence for the cooking of starchy foods (e.g. tubers) in hearths from about 120-65 kyr ago found in the Klasies River Cave in South Africa (Larbey et al. 2019). Cooking allowed us to do the work of chewing and digesting outside the body and it has been speculated that this "out-sourced digestion" was redirected to increasing our brain size and thus made us humans (Wrangham 2009).

Food remains from archeological finds

The study of paleoethnobotany archaeology, past human-plant interactions from plant remains from archeological sites, provides insights into the role of plants in daily life, diet, environment, and ecology of the time (Pearsall 2017). At least 2.6 million years ago, hominins shifted away from the consumption of nuts and berries toward eating meat (Ferraro et al. 2013; Pobiner 2016). The use of palaeoproteomics, which involves the extraction and identification of protein from ancient dental calculus of humas, provided evidence of milk consumption in East Africa at least 6-7 kyr ago (Bleasdale et al. 2021). Proteomic analysis of dental calculus from people who lived in the western Eurasian steppe during the Early Bronze Age between 3,300 to 2,500 BCE afforded evidence of milk consumption (Wilkin et al. 2021). High-altitude alpine dairying traces found on pottery date to the Iron Age (approximately 1,200-600 BCE) (Carrer et al. 2016). An archeological excavation revealed a 2,000 year old "ancient street food shop" in Pompeii, which had remnants of duck, goat, pig fish, and snails in addition to crushed beans (Mark 2020; Oxner 2020). Data providing evidence for storage of bone marrow, degradation processes for bone marrow, and delayed consumption of bone marrow have been obtained from an 420-200 kyr Israeli cave site (Blasco et al. 2019).

Food eaten by the early explorers

The Vikings, even at sea, would hang their catches of fish in the riggings of their ships to dry them in the sea winds (Coglan 2017). Amundsen the first explorer to reach the South Pole, having lived with the Inuit in the Arctics and familiar with the survival in a harsh environment, had nutritious and balanced foods prepared by him and his team at their base camp. Amundson believed that pemmican (ground, dried beef with 60% added beef fat and seasoning, originating from the Cree Indians of North America) that he chose for his team made a crucial difference to their success (Noyce 2011). Indeed, pemmican has been a food of sustenance in cold harsh climates and in emergency provisions. It has been used by indigenous people, explorers, fur traders, military and police (Ngapo et al. 2021). It is useful to refer to the learnings from early trade routes and the related high engagements of various cultures and their foods, such as the ancient "Silk Road" from China to the Middle East and Europe starting from the second century BCE which existed over 1,000 years (Hermes et al. 2018; Peters 2021), to understand human dietary intake in urban and nomadic communities.

Food processing and preservation

Archeological discoveries provide information about the evolution of food processing and preservation through history in various cultures, and upon which much of modern food systems have been developed. Food preparation and processing today has been built on historical knowledge acquired through the ages, including how to cook, transform, preserve and store food safely (Floros et al. 2010; Hall 1989). It has drawn upon the food cultures of many ancient civilizations (Dunkel et al. 2018; Erdkamp, Ryckbosch, and Scholliers 2019). Preserved foods have played a significant role in human history from enduring harsh conditions to expeditions in the unknown. The current SARS-CoV-2 pandemic exemplifies this even today when people started stock piling preserved, durable foods (Knorr and Khoo 2020). This is a current day example of what was called "searching for ways to preserve life by preserving food" (Shephard 2000). Table 1 lists the reported times on oldest evidence of human use of unit operations. Selected processes for

Table 1. Reported times on oldest evidence of human use of unit operations.

Unit operation	Time	Reference
Mechanical		
Cutting, cracking, scraping, skinning, peeling	3.39 million years	Braun et al. 2019; McPherron et al. 2010
Grinding	30 kyr	Revedin et al. 2010
Milling	28 kyr	Lucas 2011
Crystallizing	30 kyr	Shephard 2000
Thermal		
Drying	>12 kyr	Nummer 2002
Dehydration	>20 kyr	Revedin et al. 2010
Cooking, roasting, steaming	790 -780kyr	Pobiner 2016; Roebroeks and Villa 2011; Wild 2019
Concentrating	420-200 kyr	Blasco et al. 2019
Smoking	most likely same as cooking	
Frying	>2.5 kyr	Morton 1998
Baking	14.4 kyr	Arranz-Otaegui et al. 2018
Cooling, freezing	> 5 kyr	Kjorstad 2020; Shephard 2000
Biological		
Fermenting	> 9.2 kyr	Boethius 2016
Starch converting	9.5 kyr	Dietrich et al. 2019
Curdling	5.5-2.0 kyr	Bela Szecsi and Harboe 2013
S		
Chemical		
Salting	>6.0-5.5 kyr	Weller and Dumitroaia 2005
Sweetening (honey & sugar)	>8.0- 4.0 kyr	Galloway 1989; Germanidou 2020
Pickling	> 3.0 kyr	Shephard 2000
Storage & Packaging		
Soil, stones, animal skin & water storage	420 kyr	Blasco et al. 2019
Wood packaging	>3.5 kyr	Smyth et al. 2019
Pottery packaging	9.0 kyr	Liu et al. 2019

Note: The information is rather fragmented and scarce. It is an incomplete history and that provided is only reliant on literature data available.

various raw materials used through history are given in Table 2. Examples for historical and indigenous food processing/preservation methods applied are provided in Table 3. These aspects are covered in more detail below.

Mechanical processes

Cutting & cracking, scraping and skinning, peeling

Excavations from the Kuahuqiao site in Zhejiang province China suggest that wooden tools made of softwood were used to de-husk or grind seeds and that wood fibers were mixed with seeds and heated in pots (Yang and Jiang 2010). Pottery dated from 7,000-5,500 BCE that was found in different Chinese archeological sites was most likely used for boiling or processing various plant sources (Liu et al. 2019). Peeling and cutting of roots and tubers to remove undesirable or toxic substances were carried out since the onset of availabilities of tools. Immersion in liquids, animal skins or soil were also used after early preservation processes such as root or tuber peeling, cutting and soaking were carried out to remove undesirable or toxic substances (Cristiani et al. 2018; Park, Hongu, and Daily 2016).

Pounding, grinding and milling

Pounding and grinding implements have been found in several Paleolithic sites across Europe which suggests that

Table 2. Examples of sources used for historical and indigenous food processing operations.

Source	Process/Unit operations
Physical implements	
Stone tools	Cutting, peeling, de-hulling, scraping, skinning, gutting, cracking, pounding, pressing, grinding, milling
Natural physical elements	
Sun	Drying, concentrating, crystallizing
Wind	Drying
Fire	Heating, cooking, boiling, simmering, roasting, grilling, baking, frying, smoking, steaming, concentrating, drying, structuring
Water/snow/ice	Storing, cooling, freezing
Soil	Protecting, storing
Biological agents	
Microorganisms / Mixed microbial cultures	Fermenting (single organisms, multiple mixed or multiple subsequent), bio-converting, brewing, acidifying, modifying
Enzymes	Bio-converting (starches, proteins), coagulating (milk), preserving (milk, honey)
Soil	Fermenting, storing
Chemical agents	
Acids	Acidifying, pickling, curing
Salt	Dewatering, preserving
Sugar & honey	Dewatering, crystalizing, coating
Essential oils	Preserving
Spices	Preserving
Various anti-microbials (ethanol, natron, saltpeter, tannins, polyphenols)	Preserving

Table 3. Examples for historical and indigenous food processing and preservation technologies applied to specific raw materials.

Technologies	Raw materials
Conversions using a combination of physical/chemical processes	
Soaking or drying & grinding	Seeds or cereals
Concentrating & crystallizing	Sugar or honey
Drying & smoking	Nuts, cereals, fish or meat
Pressing & drying & pressing	Meat
Salting & drying	Fish or meat
Crushing & boiling & cooling	Bone marrow
Conversions using a combination of physical/chemical and biological processes	
Fermenting & curdling & drying	Milk
Salting & fermenting	Fish or vegetables
Cooking & fermenting & wrapping (flavoring, absorbing ammonia)	Fish or soybean
Grinding & mashing & filtering & fermenting	Maize
Dehulling & milling & fermenting & steaming	Rice
Pressing & fermenting	Fruits
Steaming & fermenting	Starch rich materials
Cooking & fermenting	Soybeans, wheat, oats, rye, tapioca
Cooking/steaming & fermenting, concentrating/ boiling & drying	Soybeans
Grinding & boiling & fermenting (mixed and subsequent)	Malt & wheat
Sprouting & drying Mashing & boiling & cooling & fermenting	Malt
Brining & gutting & brining & fermenting	Fish
Cutting & beheading &placing in sand/soi l& fermenting & cutting & drying	Fish
Cutting & digging in soil & fermenting (mixed cultures)	Meat

processing of plants was practiced by hunter-gatherers (Valamoti et al. 2020). Grinding stones and pestle were found from the Early Upper Paleolithic site (Longo 2016). From the Early Neolithic Göbekli Tepe site in Anatolia, Turkey, numerous mortars, pestle, hand stones and grinding slabs have also been found (Dietrich et al. 2019).

Stone-tool-assisted consumption of animal tissues occurred before 3.39 million years ago at Dikika, Ethiopia (McPherron et al. 2010). Tools could be used for cutting and cracking bones, skinning and scraping meat, extracting bone marrow, and crushing the bones for fat recovery. Grinding has been used for vegetal products since ancient times. Grass and grass seeds consumption and grinding have been indicated in Mesolithic Mediterranean (Cristiani et al. 2018). Grinding stones from the Neolithic age in Greece were applied on de-husked cereal grain or for processing grains that were still in hulls (Chondrou et al. 2021). Cereal grinding was a common practice in Europe at least 30 kyr ago (Lucas 2011; Revedin et al. 2010). There was evidence of starch grains on grinding stones found in this period in sites in Italy, Russia and the Czech Republic. The flour could have been used for the preparation of porridge, but also as raw material for bread (Revedin et al. 2010). The stone tools from the Early Neolithic Göbekli Tepe site in Anatolia, Turkey, are a possible indication for larger scale flour production from approximately 9.0-10.0 kyr ago (Dietrich et al. 2019). Li et al. (2020) demonstrated the morphological differences of starches resulting from wet (pre-soaking) or dry (pre-drying) grinding of rice and concluded, based on experimental work, that dry grinding was a common practice at Chinese sites as early as 7,000 BCE. Early rotary mills dated to the fifth century BCE, indicates evolution from hand mills to mill powered by animals ("beast mills"), water or wind (Lucas 2011).

Separating and crystallizing

Natural crystallization of honey was used and also heat induced crystallization for covering fruits (Shephard 2000) as edible coating for reducing changes in quality due to protection of the fruit matrix. Churning fermented milk to separate butter from defatted sour milk has been used in Ethiopia (Kuyu and Bereka 2020).

Recovery and processing of bone marrow, processing of pemmican by the natives of the Great Plains of North America, as well as early butter separation processes by beating milk in animal skins (Blasco et al. 2019; Shephard 2000) are early indications of food concentration. Ancient butter churning in an animal skin vessel progressed to the use of a keeler, a wider shallow coopered tub, followed by a shallow ceramic-redware-setting pan which had better conductivity for cooling. A shell shaped wooden skimmer was used to skim off the cream that rose to the top of the vessel (Wood 2009).

Current mechanical processes and future uses

All the above processes are still in use. Cutting materials (e.g. metal, ceramics) and methods (e.g. water jet cutting) have been improved. The pounding of veal meat is still an essential step in preparation of the "Wiener Schnitzel". Separation processes have been advanced, especially through the development of centrifuges. The most important development in cream separation technology was the continuous centrifuge developed by Gustaf De Laval in 1878 (Wood 2009), which is still in use today. In addition, membrane separation processes (Charcosset 2022) have taken a prominent role in separation operations, including the separation of desired or unwanted food constituents (e.g. concentration, demineralization, clarification, fractionation, cold pasteurization). A shearing device has been used to facilitate separation of a wheat dough into a gluten rich fraction and a starch phase (Peighambardoust and van der Goot 2010). Physical disruption of flour under high pressures, using a microfluidizer, has been suggested as a means to facilitate the isolation of protein and starch for production of these separate ingredients with improved functionality (Guraya 2002). An ultrasound assisted process for improving vegetable oil separation uses standing waves to improve the recovery of oil from oil bearing material (Augustin et al. 2012).

Thermal processes

Drying and dehydration

Drying is the oldest thermal preservation process. The early drying processes include sun drying of fruits, vegetables, grain, fish and meat to air drying of fish and meat in the wind (e.g. stockfish). Other drying processes include the use of drying in combination with salt or fermentation

(Asogwa, Okoye, and Oni 2017; Leigh and Turner 2020; Naumann, Price, and Richards 2014). Later, hot-air dehydration was used (e.g. hardtack or ship biscuit as a staple of sailors and explorers due to it extended shelf life and lower weight), or a combination of drying and smoking above fireplaces (Shephard 2000), or salting, drying, pressing, drying and pressing/spicing of meat (e.g. Pastirma). At least 30 kyr ago, grinding of grains took place in Europe, which most likely involved hot air dehydration of grains or roots/tubers prior to further processing (Revedin et al. 2010). During the time of replacements of Neandertals by modern humans 50-38 kyr ago, mammoth and reindeer were identified in the diet at various European sites and these meats might also have been preserved by use of fire (Revedin et al. 2010). Active drying of foods in the sun was practiced by Middle Eastern and Oriental cultures in 12,000 BCE (Nummer 2002).

Salt and natron (mixture of sodium carbonate and sodium bicarbonate) were applied for dewatering of meat mummies. The preserved food was provided for deceased Egyptians in ancient times (Clark, Ikram, and Evershed 2013). The early use of bone marrow, possibly by boiling scattered bone fragments and cooling the resulting fat/grease, has been considered as similar to use of pemmican in the Great Plains of North America (Noyce 2011). Marco Polo described how Mongol riders in 1280 carried blocks of sun and wind dried curdled milk which they then diluted with water (Shephard 2000). Dry mountain air was also used to dry meat (Shephard 2000). Sun drying of algae from an Africa site close to Lake Chad and of the yellow-green Chlorella species and the "floating garden" by indigenous Mexican inhabitants of Tenochtitlan (now Mexico City) are early evidence of a now "re-discovered" food source (Farrar 1966).

Freeze drying was used by indigenous cultures of South America living at high altitudes and by natives of North America (Cartwright 2015; Earle 2010; Hartel and Hartel 2008). Freeze drying of cultivated potatoes in southern Peru and Bolivia is traditionally practiced to produce chuňo. Boiled chuňo is said to be stable for 10 years (de Haan et al. 2010). The freeze-thaw cycles that hypocotyls of maca, *Lepidium meyenii Walpers* (Brassicaceae), are exposed to in the high plateaus of the Peruvan central Andes, result in the formation of bioactive macamides during traditional drying (Esparza et al. 2015).

Cooking, roasting, steaming and concentrating

Early evidence for the likely use of cooking vessels for cooking of meat and roasting nuts, tuber and seeds dates back to 780-790 kyr ago (Pobiner 2016; Wild 2019) . Indigenous communities around the world have been cooking and boiling food, including the Africans (Asogwa, Okoye, and Oni 2017), Inuit communities (Harry and Frink 2009), the Chinese (Liu and Reid 2020), the Vikings (Kjorstad 2020), and native Americans (Leigh and Turner 2020; Park, Hongu, and Daily 2016). Cooked starchy food from ca. 120 to 65 kyr ago has been identified from fragments of charred plant tissue (parenchyma) from cave and rock shelter hearths from the Klasies River site in South Africa (Larbey et al. 2019).

Steaming food, using red-hot rocks dropped into a wooden box with clams or roots, was practiced by indigenous people of North-Western North America (Leigh and Turner 2020). Concentration of bone marrow and subsequent grease rendering by early humans as well as the production of pemmican, a combination of dried meat and fat by indigenous North American cultures (Blasco et al. 2019) are evidence of early production and preservation processes for energy dense foods. Indigenous African cultures were cooking and thus concentrating butter for preservation purposes (Amamcharla and Singh 2022; Kuyu and Bereka 2020). The rendering of shea butter was based on ancient knowledge passed down from mother to daughter. The fruits are pulped to remove the nuts, which are roasted/smoked, then crushed with a stone, then pounded in a mortar with a pestle to produce the paste. To recover the shea butter, water is added, and the paste is beaten to form a foam that floats to the surface (Elias and Carney 2007). Steaming of wheat foods (buns, breads, "mantou") have been part of traditional Chinese cuisine for many centuries (Zhu 2014). Although there is some controversy about the origin of idli (steamed rice cake), there are suggestions that it came to India in 920 BCE from present day Indonesia (Pezarkar 2017).

Smoking

Smoking, a combination of drying and chemical preservation, was carried out by hanging food (mainly fish and meat) over open hearths, or using various kinds of wood, charcoal or peat (Leigh and Turner 2020; Noyce 2011; Shephard 2000). The archeological site at Lake Biskupin in Northeast Poland delivered 43 holes and 16 hearths from the ninth century BCE, which were considered to have been used for mass production of smoked fish. Applying the old techniques, fishes (e.g. pike, bass, bream) were scalded and gutted, then smoke dried over the open hearths at around 100 °C and then hung on a rod in the holes over smoke of oak sticks and green juniper. The holes were covered with wood or straw and fish were smoked for 2 hours to produce golden brown, smoked fish. Large mediaeval smokehouses for red herring processing and preservation had been set up in Scotland (Shephard 2000). Reindeer herding has been practiced for more than 1,200-2,000 years and reindeer meat has traditionally been smoked in a tent by Artic indigenous people (e.g. traditional Sami tent – the lávvu) (Hansen, Moldenaes, and Mathiesen 2019).

Roasting

Hominins have been roasting nuts, tubers and seed about 780 kyr ago (Wild 2019) . Inuit as well as the early inhabitants of North America have roasted fish and meat, a tradition that is repeated annually with the Thanksgiving turkeys (Park, Hongu, and Daily 2016; Spray 2002). Traditional Laplander populations of Scandinavia still spread fish fillets on wooden boards which are then tilted toward an open fire. In Lake Chilwa, Malawi, the traditional process for fish smoking was in open fire smoking mud kilns (Lipato and Kapute 2017). Coffee roasting in perforated pans was first recorded during the Ottoman Empire in the 15th century. Doner kebab, shawarma, gyros, or even tacos al pastor, stacks of meat slices roasted on a turning spit, originating food from the same time period, are still a popular staple street food in many parts of the world.

Frying

It is assumed that the first record of frying food was given by Leviticus in the 3rd book of the Old Testament, who distinguished between bread baked in an oven or "in the pan" (Morton 1998). Deep frying for producing frybreads was also used as native American food (Park, Hongu, and Daily 2016), and by the Vikings and early Chinese dynasties (Kjorstad 2020; Yu, Rahman, and Lou 2019).

Baking

Archeobotanical evidence reveals the origin of bread is from14.4 kyr ago (Arranz-Otaegui et al. 2018). Ground vegetal products have been used for bread making, either fried or fermented or baked (Revedin et al. 2010). Potatoes, corn and beans were baked by native Americans (Park, Hongu, and Daily 2016), Ethiopian flat bread is still a traditional staple (Kuyu and Bereka 2020). Baked biscuits were a key staple of ancient sailors and explorers (Noyce 2011).

Cooling and freezing

Similar to the use of fire, cooling and freezing were not invented but their potential for food preservation was rather discovered. This is another example how ancient cultures learned empirically to adapt to and to take advantage of their regional resources and conditions. This includes sun drying of mainly plant based foods in Africa, wind related drying of fish by the Vikings, cooling or freezing of fish and meat by Inuit or populations living at high altitudes as well as the use of local resources for tools, equipment, clothing and shelter/buildings. Cool moss, wet sand, wind, snow and ice and earth ware or clay pots to allow evaporation and subsequent cooling of liquids were used. Cold drinks and fruits were available in Persia, Egypt, Rome, Greece and China even in summer times, which was enabled by collecting snow from the mountains and subsequent storage in covered pits. Ice was "harvested" at large scales in the Greenland seas, in Norway and North America, and shipped to warmer regions where it was stored in "ice-houses". The Persians built "shade walls" constructions to create permanent shade at the shadow side but allowing the North wind free access. Small furrows were filled with water during the short winter and the generated ice was collected in the morning and packed in a deep trench at the shade side. At the end of the 16th century, saltpeter (potassium nitrate) and snow/cold water, or salt to reduce the temperature of ice, or saltpeter and niter (mineral form of potassium nitrate) became in use (Shephard 2000). As a means to cool air, ammonium chloride was developed and finally in 1775, Cullen reported that ice could be formed by evaporation, a technique the Egyptians had been using by putting hot water in earth ware jars and wetting the outside to induce evaporation (Shephard 2000).

Freezing in ice and snow has been applied by the Inuit, Vikings, Laplanders, Russian and inhabitants of Alpine or other harsh temperature regions (Kintisch 2015; Kjorstad 2020). An ingenious way of freezing and subsequent freeze-drying of potatoes has been developed by the native Peruvian inhabitants living at the high altitudes of the Andean Mountains, the "creators" of potatoes, by dipping them in water, leaving them overnight on the ground, removing the frozen sublimated moisture and repeating this process until the potatoes were dry (Cartwright 2015; Shephard 2000). Traditional methods for producing freeze dried potatoes in the Andes is at risk due to increasing temperatures (e.g. near Lake Titicaca) in recent times resulting in loss of chuňo, as the temperatures are not sufficiently cold to freeze the potatoes for chuňo production (Yoshikawa and Apaza 2020). The rising temperatures due to climate change are also causing problems in Artic regions in Alaska and Russia as underground freezers used to store whale meat and other traditional foods are thawing (Kintisch 2015).

Current thermal processes and future uses

All unit operations reported are still in use. The most important changes are product quality retention and safety improvements via lower temperature/vaccum processing or via shorter processing times (e.g. high temperature short time sterilization, direct steam injection, ohmic heating, microwave heating). In addition, many traditional discontinuous batch processes have been replaced by continuous ones.

Drying processes have made substantial progress although old techniques are still used. For example, Swiss "Bündnerfleisch", an air-dried beef speciality is still available today. Some traditional methods have been progressed to the preparation of new ingredients or new methods to improve nutritional value. For example, to reduce potential cancer causing agents, smoking temperatures (and sometimes flavor agents) have been reduced and traditional smoking has been replaced by the addition of liquid smoke (Xin et al. 2021). The harvesting and drying of spirulina from Lake Chad is an example of how women of the Kanembu tribe are transforming a traditional practice for drying of spirulina into paste, which is now turned into nutritional tablets for Western health stores (European Commission 2020).

New hybrid technologies have been developed for heat sensitive food stuffs (Chou and Chua 2001). However, the use of sun and wind as energy sources are still under-explored. More sun and wind drying operations are needed. An issue, due to the slow reduction of the water activity of the materials, is resulting microbial contamination and quality deteriorations, and more efficient drying alternatives are urgently sought. A unique solar dehydration system was developed (Mbuge et al. 2016) by applying a super-water absorbing gel within the air stream and using a solar energy driven ventilator to improve air flow and then drying the gel with solar energy again. Similar systems could be envisioned for wind drying processes, including wind driven ventilators and water absorbents. Freeze dehydration is still an energy intensive and time consuming process. Recent attempts identified for possible routes for improvements include ultrasound assisted freeze dehydration (Schössler, Jäger, and Knorr 2012), high pressure shift freezing, or spray freezing (Volkert et al. 2008). Ultrasound assists traditional air drying as well as freeze drying, enabling energy savings, increased throughput and reduced drying time at low temperature (Sabarez, Swiergon, and Knoerzer 2019).

Energy efficient-improved cookstoves for almost three billion people worldwide still rely on open fires. There are improved cookware materials or heat transfer materials such as marble or soapstone (Roos et al. 2016). Better understanding of availabilities of nutrients and energy depending on different processing and preparation methods (Carmody and Wrangham 2009) are needed. These include understanding effects such as high hydrostatic pressure-induced ("cold cooking") gelatinization of proteins and poly saccharides (Bauer et al. 2004; Knorr, Heinz, and Buckow 2006), and the benefits of pulsed electric field (Barba, Parniakow, and Wiktor 2020), including subsequent reduced fat uptake of potatoes during frying. Other examples for future considerations and improvements include the use of hot stones or other heat absorbing materials for heat transfer (e.g. as still in use for "Raclette" in Switzerland), high hydrostatic pressure-assisted cooling, freezing and thawing (Cui et al. 2019; Schubring et al. 2003; Urrutia Benet, Schlüter, and Knorr 2004), solar energy-driven food processing equipment, the "hurdle concept" (Leistner 1995), and intermediate -moisture foods (Karel and Heidelbaugh 1973). The principle of cooling via evaporation as traditionally applied by cooling liquids in wetted clay containers is worth reconsidering.

Biological processes

From a food science and food biotechnology point of view, biological processes for food are ubiquitous in nature. It is likely that our ancestors learned to use biological processes for food by trial and error. Fermentation is a commonly used method for food processing today (Steinkraus 2002) due to the industrialization of indigenous fermented foods (Steinkraus 1996).

Fermentation processes

Some anthropologists believe barley was made to produce beer in 10,000 BCE (Nummer 2002). The world´s earliest evidence of fermentation so far has been identified in a 9.2 kyr old construction used on the east coast of Sweden for the fermenting of fish (Boethius 2016). Fungi and bacteria were the most common microorganisms involved, either in aerobic or anaerobic processes. Yeast and mold, or a consortium of heterofermentative lactic acid bacteria and yeasts have been involved in ancient food fermentations (Venturini Copetti 2019). The benefits of fermentation include better food safety and longer shelf life, improved sought-after quality properties such as taste, flavor and texture, partial degradation of toxic or harmful substances, sustainable and low energy consumption, and food products that meet demands for natural foods (Vogel et al. 2011).

Fungi. Yeasts (unicellular organisms) have been used for fermentation of starch-rich raw materials and for sugar-rich plant foods by indigenous communities (Djien 1982; Park, Hongu, and Daily 2016). Fermentation is often preceded by soaking, cooking and/or germination to increase availabilities of plant constituents (Asogwa, Okoye, and Oni 2017). The Incas prepared a mild alcoholic drink (Chicha) by chewing maize and then leaving the pulp to ferment. Bread and alcoholic beverages existed in early populations going back to at least 10 kyr (McGovern 2017; Shephard 2000; Preedy 2009; Rose 1982). Ethanol was used early for preservation and storage of foods (Shephard 2000). Mead, a fermented alcoholic honey drink, dates back to around 7,000 BCE and remnants of a fermented mixture of wild grapes, honey and rice (a "wine-mead-sake") product that was found in pottery jars in Northern China is considered the likely oldest alcohol containing beverage (Vidrih and Hribar 2016). Mead was later produced in ancient Egypt, Greece, the Roman Empire and medieval Europe (Vidrih and Hribar 2016). Evidence of the use of *Saccharomyces cerevisiae*, the principal yeast used in modern fermentation, was obtained from remnants in early wine jars in Egypt, suggesting it was employed for wine fermentation from 3,150 BCE (Cavalieri et al. 2003). A diversity of *Saccharomyces cerevisiae* strains has been found in Sub-Saharan traditional indigenous foods and beverages (Johansen et al. 2019). There are also many yeast-based indigenous fermented products in Asia including fermented pancakes, bread and rice wines (Aidoo, Rob Nout, and Sarkar 2006). Many of the tropical based fermented cassava foods (e.g. gari, fufu, lafun, chickwanghe, agbelima, attieke and kivunde in Africa, tapai in Asia and 'cheese' bread, and 'coated peanut' in Latin America) are fermented by yeasts and bacteria (Ray and Sivakumar 2009).

As for mushrooms, the total number of mushrooms on earth is estimated to be 140,000 and of these only 10% is known. The group of edible macrofungi include at least 1,000 to 2,500 species, with only about 25% being now widely accepted as food (El Enshasy et al. 2013; Jabłońska-Ryś et al. 2019; Kirk et al. 2008). Early humans must have tested mushrooms by trial and error to distinguish between edible, poisonous and psychedelic ones, and they also learned to use the poisonous ones for fishing and hunting. A recent review of 2,786 mushrooms species from 99 countries found that 2,189 are edible and of these 2,006 were considered safe for consumption (Li et al. 2021).

Puffballs, easy to recognize by their round shape, were likely the first edible ones to be used as food and their remains have been found in Paleolithic settlements (Kiple and Ornelas 2000). Remains such as fungal spores in ancient dental calculus potentially indicate bolete mushroom use in northern Iberia (El Miron cave, Spain) during the Magdalenia period between 17 and 12 kyr ago (Kotowski 2019; Power et al. 2015). Among the Ötzìs (the ice-man) equipment, three fungal objects were identified with one most likely being used as medicine (Kotowski 2019). Mushrooms are considered historical bio-factories for medicines (El Enshasy et al. 2013). Lactic acid fermentation of mushrooms has also been practiced as a way of preserving mushrooms (Jabłońska-Ryś et al. 2019). Edible mushroom mycelia have been used for fermentation of soybean, bread, cheese and alcoholic foods to produce functional food materials (Matsui 2010; Suruga, Tomita, and Kadokura 2020). Shiitake mushrooms have been fermented with different microbial species (*Saccharomyces cerevisiae, Aspergillus oryzae, Aspergillus niger and Lactobacillus plantarum*) and it was found that umami flavor was enhanced by *Lactobacillus plantarum* (Chen et al. 2021).

With respect to the use of mold, soy sauce was invented in China over 2,500 years ago and the use of koji was also used as a digestive aid at around that time. The most common mold used for koji production is *Aspergillus oryzae* (Zhu and Tramper 2013). Apart from *Aspergillus oryzae*, other molds including *Aspergillus sojae*, and other Rhizosopus sp. are used as the starter for preparation of koji (which contains amylolytic, lipolytic and proteolytic enzymes) for a range of Asian fermented food products such as soy sauce and soy paste, sake, and rice wine (Endo et al. 2014; Venturini Copetti 2019; Yulifianti and Ginting 2018).

According to the International Dairy Foods Association, it is not exactly known who made the first cheese, but ancient records have cheesemaking occurring more than 4,000 years ago. It is suggested that Asian travelers introduced cheesemaking to Europe (International Dairy Foods Association 2022). Abundant milk fat residues in pottery vessel remains, assumed to have been used for separating curds from whey, provide evidence for cheese making in the sixth millennium BCE in northern Europe (Salque et al. 2013). Brie and Roquefort date from the eight century, Gorgonzola from the ninth century and Neufchâtel from the eleventh century (Desmasures 2014; Leclercq-Perlat 2022*). Penicillium camemberti* or/and *Geotrichum candidum* have been used for surface-ripened white mold soft cheese. The mold on the cheese surface gives these cheeses their specific appearance. Internally mold-ripened cheese such as blue cheese are ripened with *Penicillium roqueforti*. Other molds encountered mainly on the rind of semi-hard cheese made from uncooked rennet curd include *Sporendonema casei and Fusarium domesticum, Chrysosporium sulfureum* and *Mucor fuscus* and *Mucor plumbeus* (Desmasures 2014; Leclercq-Perlat 2022).

Bacteria. Lactic acid bacteria preserve a wide range of foods such as cabbage (e.g. sauerkraut, kimchi), fermented pickles (e.g. cucumber), cereal yoghurt (e.g. ogi, uji), sourdough bread and bread-like products made without wheat or rye flours (e.g. idli, puto), fermented milks (soured milk, yoghurt, kumiss, kefir, cheeses) and milk-wheat mixtures (e.g. kishk, trahanas), protein-rich vegetable products (e.g. tempeh), sauces and pastes produced by fermentation of cereals and legumes (e.g. miso, Chinese soy sauce), fermented cereal-fish- shrimp mixtures (e.g. baloo, burong dalag) and fermented meat such as salami (Caplice and Fitzgerald 1999; Di Cagno and Coda 2014; Djien 1982; Kurmann, Rasic, and Kroger 1992; NRC 1992; Steinkraus 1983), although often there is often a consortia of organisms involved in fermentation. Pickles preparation by anaerobic fermentation of vegetables, fruits, fish and meat predates to 2.4 kyr BCE (Behera et al. 2020).

Acetic acid bacteria are associated with vinegar production. The history of vinegar production dates to around 5,000 BCE. Vinegar was and still is considered a low value product resulting from low cost or agricultural and horticultural surplus raw materials (Solieri and Giudici 2009). It can be assumed that spontaneous vinegar production went hand in hand with wine making, originating from the Neolithic period (8.5-4.0 kyr BCE). This was most likely in Persia (now Iran) about 6.0 kyr BCE. Clay used to be added to wine as a “stopper” to prevent the conversion from alcohol to aerobic acetic acid fermentation. Egyptians were probably the first to use true vinegar, as revealed from vinegar residues in ancient Egyptian urns from 3,000 BCE. Hippocrates of Kos (460-377 BCE) prescribed vinegar as the main remedy against a number of diseases including the common cold and cough. A soup called Spartan broth was made from vinegar, pork, salt and blood. Romans boiled soured wine in lead pots to produce a sweet sirup with high lead concentration, which contributed to lead poisoning of the Roman aristocracy (Mazza and Murooka 2009; Solieri and Giudici 2009). The Gothic Bible translated by Wulfric between 1100-1140, was the first to mention vinegar in northern Europe. Vinegar was then used as a pickling agent, to preserve meat, fish and other foods (Kiple and Ornelas 2000). It is of interest that the Orleans method for vinegar production, described at the beginning of the 19th century, uses wood shavings/chops to increase oxygen access and to provide a support for microbial biofilms is still in use (Bhat, Akhtar, and Amin 2014).

Mixed cultures. Mixed cultures of fungi and bacteria were applied either together or in sequence, in addition to organisms existing in mixed organic environments such as soil, with protozoa, bacteria, fungi and algae growing in various relationships to each other (NRC 1992; Rose 1982; Shephard 2000). Mixed microbial cultures exist in combination, such as fungi and bacteria (e.g. ragi), or fungi (*Aspergillus oryzae*) firstly producing amylases and proteases in soybeans (koji) followed by a mixture of bacteria and fungi followed by a mixture of bacteria and fungi (yeasts). The use of mixed cultures resulted in products like miso and shoyu (Djien 1982; Hesseltime 1992). Soil, as a mixed system of organisms, converts the inedible Greenland shark (high urea and trimethylamine oxide contents) into a nose pinching delicatesse called "hakarl". This was a practice also used in Iceland and by the Inuit. Originally, food was preserved, protected and hidden in soil in many parts of the ancient world (Shephard 2000), thus subjecting foods to an array of different organisms. Traditional beers, as the Lambic beers, have been subjected to a mixture of various microorganisms over an extended period of time for many hundreds of years (Saladino 2021). Small amounts of inoculum for fermentation, especially from bread dough, yoghurt or beer production were kept and preserved as natural starter cultures (Shephard 2000).

Enzyme processes

Food bioconversion and biological catalysis regulated by thermodynamic principles are mostly based on enzymatic reactions and these are evident in fermentations and related pretreatment processes. Within the context of this paper, enzyme processes are seen as pretreatment processes.

Amylase. The Götekli Tepe site revealed starch use by humans approximately 9.5 kyr ago. Early processes of starch conversion outside the human organisms occurred by germination (sprouting) of grain (Asogwa, Okoye, and Oni 2017). Our early ancestors also relied on grasses and grass seeds as food sources. Specimen of early hominins from approximately 2 million years ago revealed that tree leaves, fruits, wood and bark, as well as grasses and sedges were part of primitive diets (Henry et al. 2012). It seems likely that the impact of smoke induced germination (Soós et al. 2019) has also been discovered and used.

Chymosin. Chymosin, a gastric enzyme from the mucosa of newborn and adolescent ruminants, was the traditional way for milk coagulation. Using an extract made by soaking of dried stomach overnight in whey and then adding it to milk caused coagulation (Shephard 2000). Evidence of milk processing was found in cave paintings in the Libyan Sahara (5,500–2,000 BCE) and Sumerian relief and stamp seals (3,500–2,800 BCE). The first attempts to isolate the enzyme were made by Jean-Baptiste Deschamps (1804–1866) (Bela Szecsi and Harboe 2013).

Current biological processes and future uses

Fermentation processes have undergone major developments and expansions. Most noteable are fermenter design developments and the use of starter cultures (including immobilized ones). This has clear benefits regarding food safety, quality, consistency as well as the increase in using probiotics for human consumption. However, the wide regional/local product varieties based on different "in house" developed microbial mutants have been reduced as international corporations use fermentation for production of ingredients and food products worldwide.

Fermentations, as low energy and resource consuming processes, need to be expanded further and this includes their application for food waste conversions and recognition of their benefits (Teutonico 1985). New raw materials such macro-algae, water plants, grasses or plankton can possibly offer new routes for preservation agents. In addition, the vast diversity of microbial enzymes in the digestive tracts of marine animals and insects may lead to a wide array of new antimicrobials.

Peeling by mechanical means is still carried, although the use of enzyme processes has also been employed to assist in peeling. Bacterial chitin degradation (Beier and Bertilsson 2013) can be used to convert one of the most abundant biopolymers and also be applied for generation of chitosan, a biopolymer with antimicrobial potential (Raafat and Sahl 2009). Solid state fermentation process enhancements, especially for improvements of heat and mass transfer and the potential for waste conversion need to be sought. Enzymes from germinating seeds production such as chitinases offer unique antimicrobial potential (Teichgräber, Zache, and Knorr 1993). Tailored stressing of microorganisms can also offer unique reactions for further processing including the retention of antimicrobial active Lactobacilli (Ananta and Knorr 2003). Fire/smoking induced germination (Soós et al. 2019) could also be considered as a tool to generate antimicrobial biopolymers. The biodegradable plastics, polyhydroxyalkanoates and poly(ε-caprolactone), can be biosynthesized and biodegraded by various marine microbes in a wide range of marine environments (Suzuki, Tachibana, and Kasuya 2021).

The tremendous untapped potential of molds and mushrooms has been recently demonstrated (Hyde et al. 2019). There is much interest in the application of synthetic biology tools for producing food and food ingredients to transform food systems, such as precision fermentation for the production of leg hemoglobin which is used as a colorant in plant-based meat analogues (Voigt 2020).

Chemical processes

Osmotic processes

Salt. Salt (sodium chloride) has been used for pretreatment prior to drying, smoking, fermenting, and pickling, mainly for fish, meat and vegetables. Salpeter (potassium nitrate) has also been applied for curing (Shephard 2000). Historically, salt has been obtained by solar evaporation and drying from sea water, boiling down water from brine springs and mining of "rock" salts (Kiple and Ornelas 2000). An early Neolithic exploitation at a salt spring in Romania indicated the first salt production in Eastern Europe was between 6,050-5,500 BCE, making it to the earliest in Europe and possibly in the world (Weller and Dumitroaia 2005). Evidence for early sea salt production in central

China around 3,000 BCE or earlier and for prehistoric salt production from sea water in the northeast of England was dated to 3,800-3,700 BCE (Sherlock 2021). Sustainable salt mining such as the mine in Hallstatt, Austria already started in the 4th millennium BCE. It is noteworthy to indicate the likely higher environmental perceptiveness of prehistoric miners of the limit of the particular landscape as the natural resources of the region were never depleted in order to provide materials (i.e. wood) needed for the mines (Festi et al. 2021; Grabner et al. 2021).

Sugar and honey. Early humans have used sweet fruit and juices such as dates, grapes, quinces and possibly made concentrates or dried products from them. The biblical Manna ("bread of heaven"), the secretion of insects that feed off the tamarisk bush was and is still collected by Bedouins. Dried dates were kneaded and heated with flour to a dry mass. This served as a dry food product and was an energy source with excellent keeping qualities. Much later, preserves and jams using sugar may have started in Scotland in 1797 (Andes 1894; Shephard 2000). The beginning of the sugar industry starting with cane sugar is reported to have been in India (now Bengal then called Gur "the land of sugar") around 4,000 BCE, where sugar cane juice was extracted and then concentrated to a granular substance called "sand sugar" (Galloway 1989). Domestication of sugar cane started in New Guinea (Deerr 1950), and subsequently the Caribbean islands became prime sugar cane producers (Shephard 2000). The sugar beet industry did not start until 1747. This was in Berlin, Germany, when Markgraf succeeded extracting a modest amount of sugar, which was later improved by breeding to increase the sugar content of the then fodder beets. The first beet sugar factory was built in 1801 (Kiple and Ornelas 2000).

Humans likely gathered honey in the same manner as their primate ancestors. The first representations of human-bee interactions are presented in cave paintings of Spain, India and Africa, dating to approx. 8,000 BCE. Excavations at Tel Rehov (Israel) uncovered at least 180 horizontal beehives made of sun dried mud, dating to the mid-10th century BCE (Germanidou 2020). Pots of honey were still preserved in tombs on Egypt from around 2,500 BCE (Gelling 2013; Germanidou 2020) due to honey's acidity, low water activity and the presence of hydrogen peroxide. Honey collecting in prehistoric West Africa dates to 3,500 years ago, and it has been used as a direct food and energy source as well as in honey-based drinks in Africa (Dunne et al. 2021). Masai warriors of Eastern Africa took no food other than honey on their long expeditions. Honey breads were common, and the Romans preserved meat in a mixture of mustard, vinegar, salt and honey. Indigenous North Americans made a sweet, dried paste of wild strawberries crushed in pure honey for winter provisions (Dunne et al. 2021).

In the first century, the Greeks made peeled and pipped quince fruits in jars filled with honey and later the Romans took advantage of the quince's high pectin content by cooking honey with pepper and spices to produce fruit preserves that were filled and sealed in jars (Shephard 2000). Fruit pulp was also mixed by the Romans with honey and spices and then sun dried. This was likely the earliest form of jam making (Shephard 2000). Mead, dating back to around 7,000 BCE was considered the earliest alcohol containing beverage (Vidrih and Hribar 2016). Current records date evidence for early beer consumption in southern China to 7,000-6,700 BCE (Wang, Jiang, and Sun 2021).

pH altering processes

Pickling possibly had its origins with food placed in wine and beer to preserve the food (Nummer 2002). Archeologists have dated pickling in Western Asia, Egypt and Greece to more than 3,000 years ago (Tisi 2018). Acetic acid and lactic acid were certainly the most common lactic acid acidification methods used for food preservation. Preservative effects of pickling and curing were due to the low pH of vinegar (Shephard 2000). The acidic environment of peat moss proved also effective, as evident by 3,500 years old bog butter findings (Smyth et al. 2019). Lye and clay were also used for pH adjustments as exemplified in wine making (Mazza and Murooka 2009; Shephard 2000). More recently, salicylic acid, sulfuric acid and burnt lime (calcium oxide) were also applied for food preservation (Andes 1894).

Antimicrobial enzyme processes

Milk and especially human milk, contain a highly effective cocktail of lactoferrin (iron-binding glycoprotein depriving microorganisms of iron), lactoperoxidase (which kill bacteria by oxidative mechanisms) and lysozyme (which disrupts bacterial cell walls). The effectiveness of the enzyme processes proved even successful at higher temperatures, as evident by the shelf life of fresh camel milk (Swelum et al. 2021). Lactoperoxidase has also been shown to play an important role in maintaining oral hygiene and alpha-amylase can hydrolyze existing biofilms of *Staphylococcus aureus* (Thallinger et al. 2013).

Antimicrobials-aided processes

Essential oils, especially from spices, have played an important role in food preservation. with the main active compounds being thymol, carvacrol, eugenol, cinnamaldehyde and linalool with clove, cinnamon, pimento, oregano and thyme (Hintz, Matthews, and Di 2015). In the case of spices, it is thymol, carvacrol and eugenol that play a major role in their antimicrobial activity (Gottardi et al. 2016; Martínez-Graciá et al. 2015). The essential oils of clove, oregano, lavender and rosemary have been reported to possess quorum sensing (microorganism-microorganism signaling) inhibitory activity (Gottardi et al. 2016). Roman consumption from all over the world was so enormous that the demand for the now unknown "silphion" (possibly genus

Ferula, perhaps variety of giant fennel) led to its extinction (Kiple and Ornelas 2000). Wooden containers of butter deposited in peat bogs of Ireland and Scotland from the Early Bronze Age revealed, besides the acidic and oxygen limited storage condition, a Maillard reaction provided an additional preservation effect (Børsheim, Christensen, and Painter 2001; Smyth et al. 2019).

Wood smoking creates diverse compounds, of which the phenolic ones (acting as antimicrobials and antioxidants), formaldehyde, acetic acid and other carboxylic acids having preservation effects (Fellows 2016). Pretreatments such as salting or curing in combination with heating reduce the water activity values and smoke constituents generated product "coating", with all contributing to preservation. In addition, antioxidative smoke constituents prevent product rancidity.

Salt and natron as well as Pistacia resin was used for preservation of meat to be placed in tombs by Egyptians (Clark, Ikram, and Evershed 2013) and turf ash for egg preservation (Shephard 2000). Hops addition to beers, as required since the start of the German purity law for beers of 1516, was also done for preservation purposes (Saladino 2021). Ethanol has antimicrobial effect on drinking waters and thus proved an effective way to provide safe liquids for sailors and warriors.

Current chemical processes and future uses

Salt, and to a certain extent sugar, which played an important role in histrorical food preservation are being reduced and replaced for human health considerations. Mechanical peeling has been replaced in industrial settings mainly by lye peeling

The medicinal properties and antimicrobial activity of honey has been documented (Mandal and Mandal 2011). However, currently commercial honey is often pasteurized requiring alternative processing routes for retaining natural enzyme activities. Antimicrobial mechanisms and inactivation kinetics of essential oils and also in combination with various gentle unit operations are poorly understood. Specific environments and plants such as peat moss, hops or wood constituents can also become valuable sources of antimicrobials. Targeted stress responses of plants can result in increased production of antimicrobial and antioxidative secondary plant metabolites (Dörnenburg and Knorr 1995).

Storage and packaging

Seasonal and bountiful natural food resources had to be preserved and stored to provide staple foods year-round (Testart et al. 1982). The oldest indication for food storage is evidence found from the Qesem Cave, Israel, where bone marrow processing and storage occurred 420-200 kyr ago (Blasco et al. 2019).

Temperature and moisture modifying processes

Underground structures using soil as a thermal insulator for cereals and grains, seeds, fruits and vegetables, and wine (Kuyu and Bereka 2020; Pinilla, Gómez, and Ospina 2020), as well as constructions above ground built with rocks, clay, wooden beams, mud, straw and wood and with suspended and tilted floors to also protect against moisture from the ground, dating back to 11 kyr have been identified (Kuijt and Finlayson 2009). The Inca, Inuit and Romans used sophisticated storage constructions even for ice and snow, and archaic Slovakians, Irish and Scots buried meat in wooden vessels with highly acidic ashes (Cartwright 2015; Shephard 2000). The Inca had sophisticated storage facilities (qollqa) allowing them to keep dried food for extended time periods. These were places on hillsides to take advantage of cool breezes and maximize storage time of perishable foods (Cartwright 2015).

Atmosphere modifying processes

The peat bogs of Ireland and Scotland used for storage of butter in wooden containers, dating back for at least 3,500 years (Smyth et al. 2019) is likely the most prominent example for prehistoric atmosphere modified storage. Storage in salt, in seawater, ice, animal skin, acidic ashes, honey, ethanol, vinegar, brines, oil, raw eggs in waterglass (water soluble alkali silicate solution) and even crystallized in sugar have been reported (Cristiani et al. 2018; Grabner et al. 2021; Kiple and Ornelas 2000; Noyce 2011; Park, Hongu, and Daily 2016; Shephard 2000), with mainly wooden or pottery containers used for storage. More recently, numerous and still edible/usable food products were revealed from sunk vessels, such as from a 170 year old shipwreck from the Baltic Sea (Londesborough et al. 2015).

Current storage/packaging processes and future uses

The constant temperatures of water (4 °C) and that of soils due to low thermal conductivity can be capitalized upon to develop alternatives to conventional electrical refrigeration and underground storage facilities, including hyperbaric food storage or even production, and possible alternatives to refrigeration in the floor beds of oceans and lakes (Mitsuda, Kawai, and Yamamoto 1972; Santos et al. 2021). The pressure temperature diagram of water also allows low temperature storage of highly valuable products also above ground at moderate pressure without undergoing phase transition or tissue damage (Knorr, Heinz, and Buckow 2006), and water binding agents have been introduced to protect against unwanted phase transitions. In addition, ethylene scavengers are used to slow down ripening processes of climacteric plants during transport and storage.

New packaging materials from food wastes or agricultural and food processing by-products including marine biodegradable from marine biopolymers (chitin, antimicrobial chitosan, alginates) are promising future routes (Guillard et al. 2018; Wang, Qian, and Ding 2018). Historic uses of fish bladder can be improved with other materials and used as biodegradable packaging materials. The natural sausage casing industry made from the intestines of animals is still used in the modern manufacturing of sausages (Koolmees et al. 2004). Various emerging methods for post-packaging microbial decontamination of food including microwave, radio frequency, infrared heating, high pressure processing and active packaging of foods (e.g. with oxygen absorbers, ethanol emitters, anti-microbial packaging, modified atmosphere) are being explored (Darsch and Moody 2009).

Interactions with surrounding environments

Humans have been reducing biodiversity throughout history although it is essential to human wellbeing. Our ancestors began affecting biodiversity 2 million years ago, which resulted in dramatic declines in mammal species in Africa (Johnson et al. 2017). This accelerated even further in step with the global expansion of homo sapiens during the past 60 kyr (Henn, Cavalli-Sforza, and Feldman 2012; Johnson et al. 2017). Records from human coastal marine settlements from approximately 10 kyr ago document human exploitation of coastal resources for food and materials, which increased through trade based colonial expansion to historical overfishing and collapse of coastal ecosystems (Jackson et al. 2001; Yasuhara and Deutsch 2022).

However, there existed societies through history who recognized the need for sustaining a balance between humans and nature. For example, the originally nomadic Aztecs founded Tenochtitlan (now Mexico City) in 1325 which reached a population of over 200,000 by 1519, bigger than any European city at that time. They developed and enforced a sophisticated zero waste system. Food leftovers and agricultural residues, as well as human excrements, were used as fertilizers. Human urine was also considered as a resource, long before the recent re-invention of its potential (Wald 2022). Burnable materials were recovered and burned at night for lightening public places. By doing so they had rather swiftly converted from a nomadic lifestyle to a highly productive and sustainable "agrarian urbanism" (Medina 2014). As another example, the salt miners from Hallstatt, Austria dealt with the surrounding and needed resources (mainly wood for construction) responsibly and sustainably for 3,500 years (Festi et al. 2021).

The White/Wiphala Paper on Indigenous Peoples´ food systems (FAO 2021) stress their basic principles as: "our Indigenous Peoples´ food system consists of food generation and production techniques that incorporate mobility and mobile livelihoods and are blended with rights and responsibility over natural resources". Currently there are more than 476 million Indigenous peoples living in 90 countries across the world (FAO 2021). It is important to note that the White Paper also indicates that Indigenous Peoples´ food systems do not follow linear value chains but emphasize circularity and comprise many ways of obtaining, preparing, storing and sharing food and by doing so also promote equitable distribution of resources and power (FAO 2021).

Some of the changes in consumption patterns in indigenous communities have had negative consequences on health outcomes and food security (Brand-Miller and Holt 1998; Browne et al. 2020; Bussey 2013; Walch et al. 2021). Several indigenous communities have used local food resources and traditional processing techniques, adapted to their agro-ecological region, to meet the nutritional needs of the population (Chadare et al. 2018). Ethnobotanical investigations into indigenous vegetables and wild relations and conservation of genetic diversity deserve attention (Nyadanu and Lowor 2015). A better appreciation of nutritious but often under-consumed wild food plants, that were part of diets and traditional food systems, will help improve nutrition and conserve genetic and cultural diversity (Pawera et al. 2020; Stadlmayr et al. 2013).

Discussion

History and developments in food processing and preservation

The preceding sections described how our ancestors processed, preserved and stored their food for survival throughout extended periods. They adapted processing and preservation of food, making use of the natural elements and availability of raw materials, to ensure that they had an adequate safe and sufficient food to tide them over the seasons and when exposed to harsh climates and environments. The most striking conclusions from the exploration into the history of food processing and preservation is how our early ancestors managed via a learning by doing approach, to create most impressive, ingenious and complex food processing, preservation, storage and packaging systems and en route to create foods many of which are still being used today.

The pounding of food raw materials to increase energy availability, shearing devices to separate protein rich and starch rich fractions from cereals, the early development of hearths and smoking devices, the use of hot stone for heat transfer and storage, the vast diversity of fermentation methods including the use of soil organisms, the early use of chymosin for milk coagulation, realizing the antimicrobial effect of spices, the use of osmotic effects of salt and sugar, or the antimicrobial effects of honey, the most useful effect of pH reduction via acetic acid and lactic acid, edible coatings with crystalized sugar and honey, the use of turf ash or water glass for egg preservation, the storage of food in fish bladder or animal intestines, as well as the use of soil and water as thermal insulators during storage are just a few examples of this creativity. It is also remarkable how our early our ancestors from different regions of the world started interacting and exchanging knowledge with each other and developed international trade routes.

It is surprising that meat, fish, and fat consumption of our ancestors was high and so was the consumption of salt, smoke products and alcoholic beverages. For example, the food rations of sailors on Spanish treasure ships (1503-1660) consisted of bread, wine, salt beef, salt cod, beans or chickpeas, olive oil and vinegar averaging to 3,630 kcal per day, 1,000 of which were accounted to wine (Hamilton 1929). One can only speculate how this was manageable for extended periods of time and why we became so "sensitive" to many of these food constituents (Gibney and Forde 2022;

Hanski et al. 2012; Ludwig et al. 2021). Reconstruction of ancient microbial genomes from human gut from 1-2 kyr ago revealed alterations to extinction in gut bacteria due to industrialization (Wibowo et al. 2021). This bacterial extinction, aside from improved sanitation, and the use of antimicrobials and antibiotics (Ramirez et al. 2020) may also be related to the reduction in biodiversity of our food supply (Heiman and Greenway 2016; Knorr and Augustin 2022).

In 2012 the Royal Society of the UK National Academy of Sciences convened a group of its Fellows to list the 20 most significant innovations in the history of food and drink. Of thesee, the food preservation related innovations were: refrigeration, sterilization, canning, the oven, baking, grinding/milling, fermentation, the pot, the knife, microwave oven, frying (Royal Society 2012). Impressive advances have been made in the areas of pasteurization and sterilization, refrigeration and freezing, extrusion processing, microwave heating as well as decanter/high speed centrifuge separation and pressure homogenization. In addition, packaging became an integral part of processing (Gould 1996, Van Boekel et al. 2010). Energy and consumer concerns aided the development of new food processing technologies with the aim of food quality retention, reduced energy and resource (e.g. water, chemicals) needs while maintaining highest food safety criteria. These new and emerging technologies include the use high hydrostatic pressure, pulsed electric fields, ohmic and radio frequency heating, irradiation, ultraviolet and infrared or pulsed lights, supercritical fluid extraction, direct steam injection and cold atmospheric plasma (Tiwari, Norton, and Holden 2014; Barbosa-Canovas, Tapia, and Cano 2000). More recently, packaging issues have become a major concern, including the lack of understanding of the principles of food processing and subsequent confusion with product formulation became an issue (Knorr and Augustin 2021b).

Building on history for sustainable food systems

The preservation of nature and the environment are non-negotiable in developing the food systems for the future. We should consider the many elements of the food system and sustainability indicators for building an enduring food supply for all (Figure 1).

Modern dietary guidelines have identified the raw material sources of foods, with an emphasis on plant-based food for healthy and sustainable diets (Cambeses-Franco et al. 2022; EAT Lancet Commission 2019) but factors such as affordability of diet for all people and cultural factors also need to be considered (Vaidyanathan 2021). Although also important, though often neglected, are the changes of availability of nutrients and energy based on different food processing and preservation methods on foods (Carmody and Wrangham 2009; Lillford and Hermansson 2021; Papathanasiou et al. 2015; Teutonico and Knorr 1985) and the need for processing to convert raw materials into consumer-acceptable food products (Knorr and Augustin 2021b; Van Boekel et al. 2010). These considerations got humankind through more than three million years through harsh climate periods and voyages. We can build on the knowledge created by our forefathers to better future-proof our food supply in the face of changing environments and climate change. This requires the development of strategies for harnessing and exploiting traditional knowledge to increase dietary biodiversity and improve food and nutritional security (Dunkel et al. 2018; Vogliano et al. 2021). This is especially so in the face of the urgent need for the

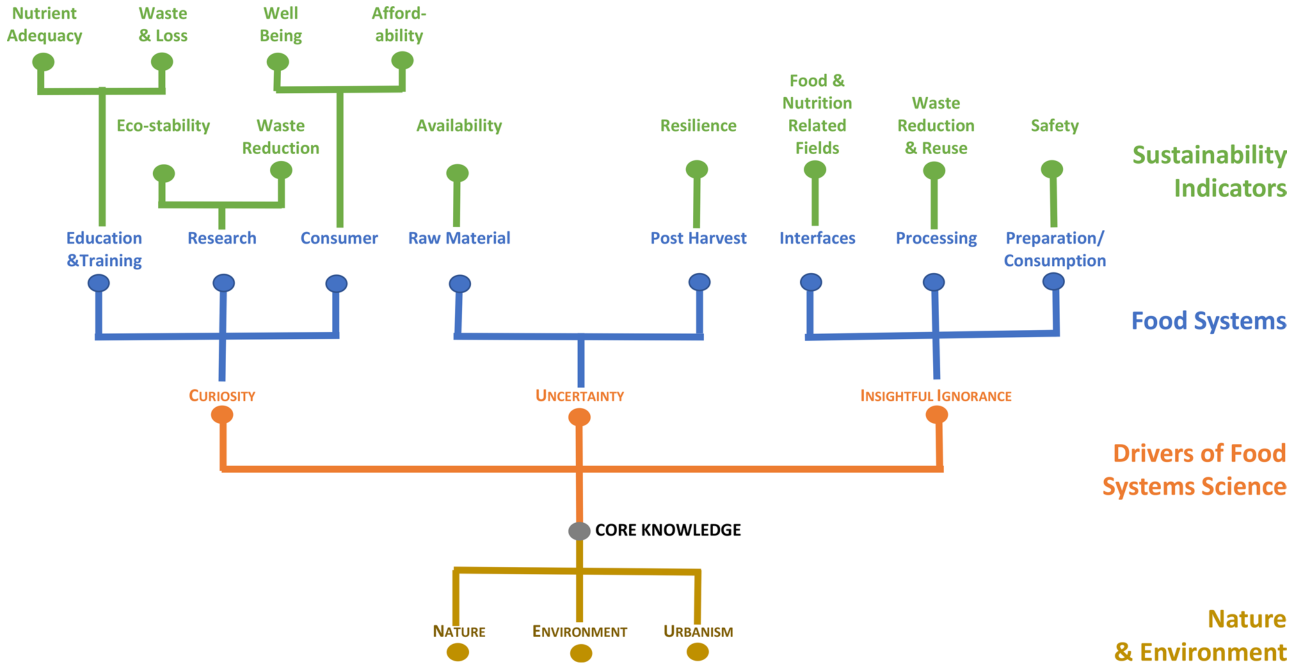

Figure 1. The Knowledge Tree – Interdisciplinary science for building future food systems. (Core knowledge includes food related sciences and crosses food inter- and intra-discipline boundaries).

world to take steps for improved climate resilient development (Intergovernmental Panel on Climate Change 2022).

Based on previous recommendation (Knorr 2018; Knorr, Augustin, and Tiwari 2020, Knorr and Augustin 2022) the following requirements still exist:

- Develop energy and resource efficient cheap cooking stoves
- Apply energy and resource efficient combinations of processes (e.g. traditional- emerging)
- Increase the use of biological processes in processing
- Develop robust, flexible and scalable processing units
- Exploit alternative energy sources for food processing operations (e.g. wind, water, solar)
- Develop sustainable food packaging systems
- Reconsider existing transportation and delivery systems
- Re-evaluate existing unit operations and processes relating to energy and resource efficiency and food system integration

Conclusion

The complex notion that human need food, and food needs nature (Batini 2021), and the fact that this is only possible if the interplay and balance of naturés vast number of species remains intact (Knorr and Augustin 2022), is the only assurance for a future of healthy and safe food supplies. There is much that can be learnt from our ancestors before modern food processing and our improved understanding today of the science that underpins new developments in food processing. Interactions between scientists and practitioners across disciplines can improve our understanding about how our ancestors lived and how they adapted to their diverse environments in various societies in different parts of the world. However, there are many gaps in the information in the history of how our food and drink evolved over time. Achieving better insights will be well-served by collaboration between food scientist, archaeologists and food historians and appropriate use of this will help build a better more food-secure future. Cross-disciplinary research at the nexus of food and anthropology will be useful for understanding the relationship of food and humans through history and make us better prepared to face the challenges of future sustainable food supplies. There is a need to bridge the gap between Western culture technical information and the wealth of technical and ecological indigenous knowledge (Dunkel 2018; Giusti et al. 2018). This should include the vast and long-standing knowledge of indigenous cultures and their cultural heritage (Dunkel et al. 2018) and as recently stated: "Over millennia, food, cooking and eating became the most powerful expression of the human imagination. So, when a food becomes endangered, another seed lost, another skill forgotten, it is worth remembering the epic story how we got here" (Saladino 2021).

Disclaimer/authors note

Different time references and dates have sometimes been used in various publications when similar events have been reported. This reflects some inconsistencies in dating of sites and estimation of time periods in the literature which we, as food scientists, cannot verify and therefore have reported the time periods provided by authors of the publications referred to.

Disclosure statement

The authors declare no conflicts of interest.

Funding

The author(s) reported there is no funding associated with the work featured in this article.

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